**VI. Biaxial:**

There are four limiting types of biaxial interference figures. Three occur when either X, Y, or Z is perpendicular to the stage and the fourth occurs when an optic axis is perpendicular to the stage. The four figures are called optic axis (OA), acute bisectrix (AB), obtuse bisectrix (OB), and optic normal (ON). The Y direction always coincides with the ON. The AB and OB figures correspond with X and Z when the mineral is negative, or with Z and X when the mineral is positive.

The centered AB is the most useful biaxial figure. From it the microscopist can determine the mineral's optic sign and approximate 2V.

2V is found by the separation of the melatopes (OA1 and OA2, Figure 9). The optic sign is found by determining whether X or Z is the AB. Figure 9 is an example of a positive mineral because we are looking down Z. Note, that at the crosshair intersection true and outcrop, which coincide with Z and Y. Addition occurs with insertion of an accessory plate when N of the crystal is parallel to N of the plate -- for instance, at the crosshair intersection. If the crystal were negative, would be replaced by at the crosshair intersection and subtraction would occur at that point.

There is no clear set of rules for locating the different types of interference figures for biaxial minerals, except for the OA figure, which is the same as in the uniaxial case - find a large crystal with small retardation. Depending upon 2V and the mineral's birefringence, different grains will exhibit different interference figures.

Uniaxial vs biaxial character can often be determined without centered figures. An isogyre that passes through the center of the crosshairs and is not parallel to a crosshair indicates a biaxial mineral.

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| **Double Refraction** All anisotropic minerals exhibit the phenomenon of double refraction. Only when the birefringence is very high, however, is it apparent to the human eye. Such a case exists for the hexagonal (and therefore uniaxial) mineral calcite. Calcite has rhombohedral cleavage which means it breaks into blocks with parallelogram - shaped faces. If a clear rhombic cleavage block is placed over a point and observed from the top, two images of the point are seen through the calcite crystal. This is known as double refraction. What happens is that when unpolarized light enters the crystal from below, it is broken into two polarized rays that vibrate perpendicular to each other within the crystal. |

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| One ray, labeled o in the figure shown here, follows Snell's Law, and is called the ***ordinary ray,*** or ***o-ray***. It has a vibration direction that is perpendicular to the plane containing the c-axis and the path of the ray. The other ray, labeled e in the figure shown here, does not follow Snell's Law, and is therefore referred to as the ***extraordinary ray***, or ***e-ray***. The e ray is polarized with light vibrating within the plane containing the c-axis and the propagation path of the ray. |  |

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| Since the angle of incidence of the light is 0o, both rays should not be refracted when entering the crystal according to Snell's Law, but the e-ray violates this law because it's angle of refraction is not 0o, but is r, as shown in the figure. Note that the vibration directions of the e-ray and the o-ray are perpendicular to each other. These directions are referred to as the ***privileged directions*** in the crystal. |

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| If one separates out the e-ray and the o-ray as shown here, it can be seen that the o-ray has a vibration direction that is perpendicular to the propagation direction. On the other hand, the vibration direction of the e-ray is not perpendicular to the propagation direction. A line drawn that is perpendicular to the vibration direction of the e-ray is called the ***wave normal*** direction. It turns out the wave normal direction does obey Snell's Law, as can be seen by examining the diagram of the calcite crystal shown above. In the case shown, the wave normal direction would be parallel to the o-ray propagation direction, which is following Snell's Law. |  |

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| **Uniaxial Indicatrix** Just like in isotropic minerals, we can construct an indicatrix for uniaxial minerals. The uniaxial indicatrix is constructed by first orienting a crystal with its c-axis vertical. Since the c-axis is also the optic axis in uniaxial crystals, light traveling along the c-axis will vibrate perpendicular to the c-axis and parallel to the  refractive index direction. Light vibrating perpendicular to the c-axis is associated with the o-ray as discussed above. Thus, if vectors are drawn with lengths proportional to the refractive index for light vibrating in that direction, such vectors would define a circle with radius . This circle is referred to as the ***circular section*** of the uniaxial indicatrix. |

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| Light propagating along directions perpendicular to the c-axis or optic axis is broken into two rays that vibrate perpendicular to each other. One of these rays, the e-ray vibrates parallel to the c-axis or optic axis and thus vibrates parallel to the refractive index. Thus, a vector with length proportional to the  refractive index will be larger than or smaller than the vectors drawn perpendicular to the optic axis, and will define one axis of an ellipse. Such an ellipse with the  direction as one of its axes and the direction as its other axis is called the ***Principal Section*** of the uniaxial indicatrix.  |  |

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| **Optic Sign** Recall that uniaxial minerals can be divided into 2 classes based on the optic sign of the mineral. |

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| * If the optic sign is negative and the uniaxial indicatrix would take the form of an oblate spheroid. Note that such an indicatrix is elongated in the direction of the stroke of a minus sign.
* If the optic sign is positive and the uniaxial indicatrix would take the form of a prolate spheroid. Note that such an indicatrix is elongated in the direction of the vertical stroke of a plus sign.
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 ***Optical Orientation***

The optical orientation of a mineral relates the orientation of the optical indicatrix to the crystallographic axes (Figure 10). The optical orientation is required to relate the optical properties to the crystal structure and is determined by using optical techniques to locate the crystal's indicatrix. Next, the crystal is x-rayed to determine the

orientation of its crystallographic axes. This information is then combined and the relationship between crystallographic axes and indicatrix determined. One major use of optical orientation is the measurement, with associated correlations, of chemistry with extinction angles on various cleavage traces (Figure 11 and 12).

The spindle stage greatly aids in determination of optical orientation. The indicatrix orientation can be rapidly and precisely found with it. Next, the crystal used on the spindle stage can be transferred to an x-ray diffractometer and the crystallographic axes located.

The optical orientation of an isotropic mineral is trivial because the indicatrix is a sphere and can be oriented in any direction. Likewise, the optical orientation is simple for uniaxial minerals. The vibration

direction is always parallel to the c-crystallographic, by definition. However, for biaxial minerals a more complex, and useful, situation exists. For the biaxial minerals it is necessary to consider each crystal system individually.

For orthorhombic minerals the three mutually perpendicular crystallographic axes, a, b, c, are parallel to the three mutually perpendicular optical directions, X, Y, Z. There are six possible relationships between these directions: (1) a=X, b=Y, c=Z (2) a=X, b=Z, C=Y (3) a=Z, b=X, c=Y (4) a=Y, b=X, c=Z (5) a=Y, b=Z, c=X and (6) a=Z,

b=Y, c=X. An example of case #6 is shown for the orthorhombic mineral andalusite in Figure 10.

In the monoclinic crystals one of the optical directions X, Y, or Z is parallel to b, the single symmetry axis. For the monoclinic mineral scolecite b=Z. Because of the monoclinic symmetry, the other two directions, in this example X and Y, lie in the plane containing the other two crystallographic axes. To complete the optical orientation for a monoclinic mineral, the angle between c and the optical direction nearest to it is usually given.

For triclinic minerals none of the optical directions coincide with any of the crystallographic axes. To relate the two, sets of axes angles must be determined between them and reported, or shown schematically in an optical orientation diagram.

Dispersion of the optical orientation can occur for monoclinic and triclinic crystals. In these systems the indicatrix actually moves as a function of wavelength. Dispersion of the optical orientation is not possible in the other crystal systems because of symmetry constraints placed upon the indicatrix by the crystal system.

The morphological correlation between the refractive indices and the crystal is an important property for mineral identification. When the smallest refractive index value is parallel to the longest dimension of a crystal, it is termed length fast. When the largest refractive index is parallel to the longest dimension of the crystal, it is termed length slow. A third possibility exists for biaxial minerals when

is parallel to the long axis of the crystal. In this case the crystal is termed length intermediate.



Figure 11. Position of the isotropic, uniaxial and biaxial minerals



Figure 12. Conoscopic view of the isogyre, isochrome and melatope.